

Directed flow at midrapidity in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions

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We analyze published data from the ALICE Collaboration in order to obtain the first extraction of the recently-proposed rapidity-even directed flow observable v_1 . An accounting of the correlation due to the conservation of transverse momentum restores the factorization seen by ALICE in all other Fourier harmonics and thus indicates that the remaining correlation gives a reliable measurement of directed flow. We then carry out the first viscous hydrodynamic calculation of directed flow, and show that it is less sensitive to viscosity than higher harmonics. This allows for a direct extraction of the dipole asymmetry of the initial state, providing a strict constraint on the non-equilibrium dynamics of the early-time system. A prediction is then made for v_1 in Au-Au collisions at RHIC.

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I. INTRODUCTION

Azimuthal correlations between particles emitted in heavy-ion collisions are a useful observable to probe the behavior of these systems [1]. Specifically, one measures the Fourier coefficient [2]

$$V_{n\Delta} \equiv \langle \cos n\Delta\varphi \rangle, \quad (1)$$

where $\Delta\varphi$ is the relative azimuthal angle between a pair of particles, and $\langle \dots \rangle$ denotes an average over pairs and collisions. The long-range part of this correlation (defined by a rapidity gap between the pair) is mostly generated by collective, anisotropic flow of the strongly-coupled matter created in the collision [3].

The most studied Fourier component is $V_{2\Delta}$ [4–6], corresponding to elliptic flow [7]. Recently it was realized that event-by-event fluctuations [2], generate a whole series of harmonics. This has triggered detailed analyses of $V_{n\Delta}$ for $n = 3$ –6 [8–13].

Neglected in these analyses is the first Fourier harmonic $V_{1\Delta}$. The observed $V_{1\Delta}$ is smaller than $V_{2\Delta}$ and $V_{3\Delta}$ [3, 10], and receives a sizable contribution from global momentum conservation [14, 15] which makes its interpretation less straightforward. Fluctuations are expected to create a dipole asymmetry in the system [16], resulting in a specific directed flow pattern, with high transverse momentum particles flowing in the direction of the steepest gradient and low p_T particles flowing in the opposite direction. Hints of this directed flow have been extracted from published $V_{1\Delta}$ data at the Relativistic Heavy-Ion Collider (RHIC) by two of the authors [17], and its magnitude and p_T -dependence were shown to be in agreement with ideal hydrodynamic calculations [18]. Note that this quantity is distinct from the directed flow observable that has been obtained in the past from measurements employing a rapidity-odd projection [19]. That rapidity-odd v_1 gives a negligible contribution to $V_{1\Delta}$ near mid-rapidity and represents different physics [20].

In this Letter, we show that data on $V_{1\Delta}$ obtained by ALICE [10] can be explained by the superposition of

two effects: global momentum conservation and directed flow. This allows for the first reliable measurement of directed flow at mid rapidity. We then carry out the first viscous hydrodynamic calculation of directed flow, and show that these data can be used to constrain the initial dipole asymmetry of the system for each centrality, putting strong constraints on models of initial conditions.

II. DIRECTED FLOW FROM DIHADRON CORRELATIONS

The standard picture of heavy-ion collisions is that an approximately thermalized fluid is created, which eventually breaks up into particles. Particles are emitted independently in each event, with an azimuthal distribution that fluctuates from event to event. This yields a two-particle correlation which factorizes into the product of two single-particle distributions [21]:

$$V_{n\Delta}(p_T^t, p_T^a) = v_n(p_T^t) v_n(p_T^a), \quad (2)$$

where the superscripts t and a refer to trigger and associated particles that can be taken from different bins in transverse momentum, and $v_n(p_T)$ is the anisotropic flow coefficient. Note that it is possible for the event-averaged correlation to not factorize even if independent emission holds in each event [21], and it is also possible for intrinsic (“non-flow”) pair correlations to factorize [22]. However, flow is currently the only known mechanism that produces a factorized correlation in the range of transverse momentum studied here (the bulk of particles). This factorization has been tested in Pb-Pb collisions at the Large Hadron Collider (LHC) [10, 12]: this is done by fitting the left-hand side of Eq. (2), which is a $N \times N$ symmetric matrix for N bins in p_T , with the right-hand side of Eq. (2), using the N values of $v_n(p_T)$ as fit parameters. The ALICE collaboration has shown that, while the data do factorize for $n > 1$, this factorization breaks down for $n = 1$ [10]. This is not surprising since there is expected to be an additional long-range correlation induced by momentum conservation that only affects the

Centrality	χ^2 , Eq.(2)	χ^2 , Eq.(3)	k [10^{-5}GeV^{-2}]	$(\sum p_T^2)^{-1}$
0–10%	6	2.0	$2.5^{+1.1}_{-0.3}$	6.2
10–20%	16	1.7	$4.7^{+1.4}_{-0.4}$	8.9
20–30%	45	2.2	$10.2^{+2.1}_{-0.5}$	13
30–40%	75	2.2	$20.6^{+3.2}_{-1.6}$	21
40–50%	126	2.4	$41.5^{+4.7}_{-3.0}$	35

TABLE I. From left to right: χ^2 per degree of freedom of the fit to the ALICE $V_{1\Delta}$ [10] (restricted to $p_T < 4$ GeV/c) using Eq. (2), and using Eq. (3); value of k from the fit; estimated value of k from momentum conservation in units of $10^{-5}(\text{GeV}/c)^{-2}$.

first harmonic [14]. The constraint that all transverse momenta add up to 0 yields a back-to-back correlation between pairs, which increases linearly with the transverse momenta of both particles. This correlation adds to the correlation from flow:

$$V_{1\Delta}(p_T^t, p_T^a) = v_1(p_T^t)v_1(p_T^a) - kp_T^t p_T^a. \quad (3)$$

(Note that the nonflow correlation also factorizes in this particular case [22], but the sum does not.) Table I compares the quality of the fit to $V_{1\Delta}$ using Eq. (2) or (3). Adding one single fit parameter k tremendously increases the quality of the fit for all centrality windows. We have checked that the values of the fit parameters depend little on the p_T window. However, the quality of the fit decreases as higher p_T particles are included, as observed for other harmonics [10]. Nevertheless, we include the entire range of values as a systematic uncertainty in Table I, varying the lower p_T cutoff between 0.25–0.75 GeV, and the upper cutoff between 2.5–15.0 GeV. Similarly, we use this procedure to estimate a systematic uncertainty in v_1 (see Fig. 2 below).

Next, we check whether the value of k from the fit is compatible with the value expected from momentum conservation. Assuming for simplicity that momentum conservation is the only source of correlation, one obtains [14] $k = \langle \sum p_T^2 \rangle^{-1}$, where the sum runs over all particles emitted in one event, and angular brackets denote an average over events in the centrality class. Since experiments measure only charged particles in a restricted phase-space window, only a rough estimate of this quantity can be made, by extrapolating from existing data. We have used the preliminary identified particle p_T spectra from ALICE at midrapidity [23], and extrapolated them outside the p_T acceptance of the detector using Levy fits [24]. In order to extrapolate to all rapidities, we have assumed for simplicity that p_T spectra are independent of rapidity, and we have used the total charged multiplicity estimated by the ALICE collaboration [25]. Neutral particles were taken into account assuming isospin symmetry, and the contribution of particles heavier than nucleons was neglected.

The resulting estimate is shown in the last column of Table I. The fit result in general has the correct size and increases with % centrality, as expected. The centrality

dependence is steeper than expected from our rough estimate, however — the fit value is larger than the estimated value for the most peripheral bin, while it is significantly smaller for central collisions. We cannot explain this, but overall the agreement is reasonable, and a discrepancy in k of this size has a very small effect on the extracted directed flow; the extracted directed flow curves with k fixed to the estimated values were also included in the systematic error band in v_1 , but only have a small effect on the two most central bins.

It has been suggested that the correlation from momentum conservation could be larger than our estimate because of approximate conservation of transverse momentum within smaller subsystems of the entire collision system—specifically rapidity slices of roughly unit extent [26, 27]. However, we see no evidence here for such an enhancement.

Thus, by taking into account the only obvious non-flow correlation, the factorization seen in higher harmonics is restored, and we can take the resulting $v_1(p_T)$ as a reliable measurement of directed flow v_1 (presented in Fig. 2 below).

III. RESULTS OF HYDRODYNAMIC CALCULATIONS

Relativistic viscous hydrodynamics has been shown to successfully reproduce v_n for $n = 2, 3, 4$ [28]. Here, we present the first viscous hydrodynamic calculation for directed flow, v_1 . In hydrodynamics, v_1 and the corresponding event-plane angle Ψ_1 are defined by $v_1 e^{i\Psi_1} \equiv \langle e^{i\varphi} \rangle$, where angular brackets denote an average over the momentum distribution at freeze-out [29]. A collision of identical nuclei at mid-rapidity has $\varphi \rightarrow \varphi + \pi$ symmetry except for fluctuations, hence v_1 at midrapidity is solely due to event-by-event fluctuations in the initial state.

In event-by-event ideal hydrodynamic calculations, v_1 was found [18] to be approximately proportional to the dipole asymmetry of the system ε_1 defined as [16]

$$\varepsilon_1 \equiv \frac{|\{r^3 e^{i\phi}\}|}{\{r^3\}}. \quad (4)$$

where $\{\dots\}$ denotes an average value over the initial energy density after recentering the coordinate system ($\{r e^{i\phi}\} = 0$).

Here, in order to make a systematic study, we use a smooth, symmetric density profile which we deform to introduce a dipole asymmetry of the desired size and orientation. Specifically, our calculation is a 2+1 dimensional viscous hydrodynamic calculation which uses as initial condition the transverse energy density ($\epsilon(r, \phi)$) profile from an optical Glauber model [30], which is deformed in a way analogous to the previous study of v_3 and higher harmonics in Ref. [31]:

$$\epsilon(r, \phi) \rightarrow \epsilon\left(r\sqrt{1 + \delta \cos(\phi - \Phi_1)}, \phi\right), \quad (5)$$

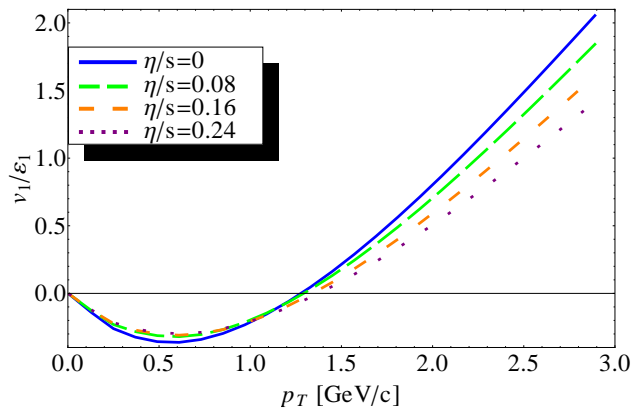


FIG. 1. (Color online) Directed flow v_1 , scaled by the initial dipole asymmetry ε_1 , in a central Pb-Pb collision at 2.76 TeV, for different values of the shear viscosity to entropy ratio η/s .

where δ is a small parameter. Both v_1 and ε_1 are proportional to δ for $\delta \ll 1$. For noncentral collisions, v_1 depends mildly on the orientation of the dipole asymmetry Φ_1 with respect to the impact parameter. Our results are averaged over Φ_1 .

Fig. 1 presents the ratio v_1/ε_1 as a function of the transverse momentum p_T for central collisions. Unlike higher-order harmonics, which are usually positive for all p_T , v_1 changes sign. The reason is that the net transverse momentum of the system is zero by construction, which implies $\langle p_T v_1(p_T) \rangle = 0$: low- p_T particles tend to flow in the direction opposite to high- p_T particles.

The harmonics v_n tend to probe smaller length scales with increasing n , and as a result are expected to have an increasing sensitivity to viscosity. Our results show that, indeed, v_1 is less sensitive to viscosity than v_2 [32] and higher harmonics [28, 31]. This insensitivity to viscosity combined with the approximate proportionality $v_1 \propto \varepsilon_1$ provides a unique opportunity to place a direct constraint on the dipole asymmetry of the early-time system.

In a realistic Pb-Pb collision, ε_1 varies from event to event. The contribution of directed flow to $V_{1\Delta}$ scales like ε_1^2 . Therefore the experimentally measured v_1 scales like the root-mean-square (rms) value of ε_1 in the centrality bin. As we shall see below, there is a wide range of predictions for this quantity. With these new data we can now quickly discern which are compatible with experiment by identifying an allowed range of values for the rms dipole asymmetry.

Fig. 2 displays v_1 versus p_T extracted from ALICE correlation data using Eq. (3). The magnitude and p_T dependence of v_1 are similar at LHC and at RHIC [17], and the mild centrality dependence, reminiscent of v_3 [8, 9], is expected since both are generated purely from fluctuations in the initial state.

The p_T dependence of v_1 in LHC data bears a striking resemblance to that predicted by hydrodynamics, Fig. 1. In a given centrality window and for a given value of the viscosity, one can tune the value of the dipole asymme-

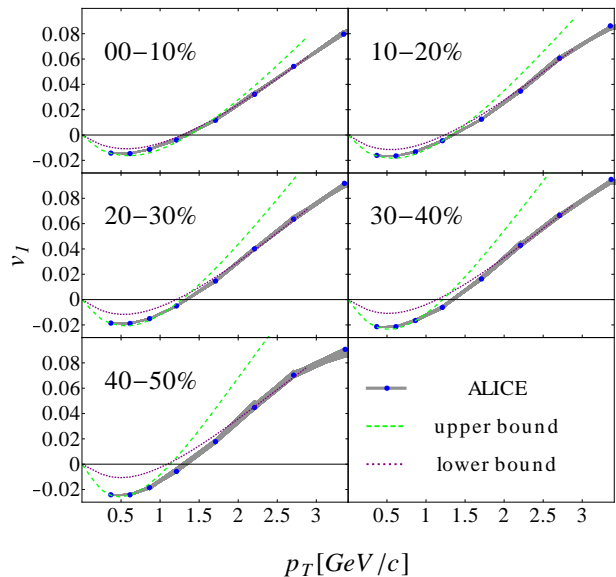


FIG. 2. (Color online) $v_1(p_T)$ in Pb-Pb collisions at 2.76 TeV extracted from correlation data [10], in various centrality windows. The shaded band represents the systematic uncertainty from the choice of p_T window used for the fit. The curves are hydrodynamic calculations where the value of ε_1 has been adjusted so as to match the data from above or below, and which were used to obtain the upper and lower bound, respectively, in Fig. 3.

try ε_1 in the hydrodynamic calculation so as to obtain reasonable agreement with data. If one chooses to match data at the lowest p_T , calculation overpredicts data at high p_T . Conversely, if one matches data at high p_T , calculation underpredicts data at low p_T . The corresponding values of ε_1 can be considered upper and lower bounds on the actual value.

The values of η/s (the ratio of shear viscosity to entropy density) implied by comparisons of elliptic flow data to hydrodynamic calculations all lie in the range $0 < \eta/s < 0.24$ [30, 33, 34]. Assuming that η/s lies in this range, we can extract an allowed range for the dipole asymmetry, using the extremal values of η/s and ε_1 that still give a reasonable fit to data. (the extremal curves used are shown in Fig. 2).

Fig. 3 displays the allowed values of ε_1 as a function of centrality, together with the rms ε_1 from various Monte-Carlo models of initial conditions. The allowed range assuming $0.08 < \eta/s < 0.16$, representing the most common values extracted from v_2 data, are also shown in a darker band, to illustrate the small effect of viscosity. Both the order of magnitude and the centrality dependence of ε_1 from Monte-Carlo models resemble the allowed values from LHC data. However, there are significant differences between the models. LHC data already exclude DIPSY [35] above 10% centrality, and the Phobos Glauber model [39] as well as a recent improved mck model with KNO fluctuations [38] over the entire

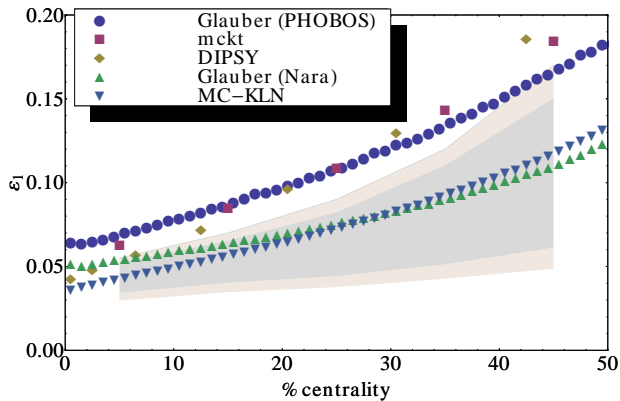


FIG. 3. (Color online) Variation of ε_1 with centrality. The shaded bands indicate the allowed regions using ALICE data in combination with viscous hydrodynamics, assuming either $0 < \eta/s < 0.24$ (lighter shade) or $0.08 < \eta/s < 0.16$ (darker shade). Also shown are the prediction of several Monte-Carlo models of initial conditions: DIPSY [35], MC-KLN (obtained from mckT v1.00) [36, 37], mckT v1.25 [37, 38], and two different implementations of the Glauber model utilizing point-like nucleons [39] or uniform disks [37]. The binary collision fraction for both Glauber models was taken to be $x = 0.18$ [40].

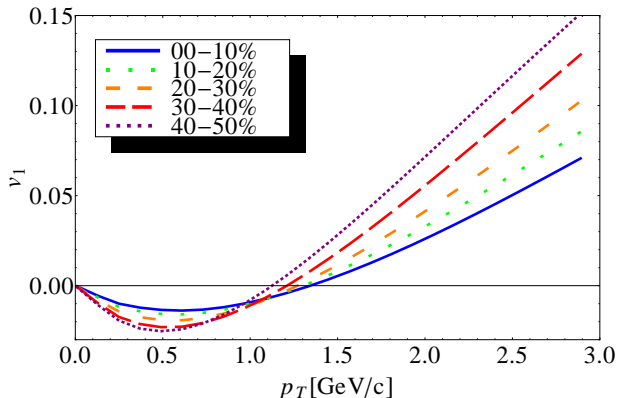


FIG. 4. (Color online) Viscous hydrodynamic prediction for v_1 in Au-Au collisions at 200 GeV in various centrality windows.

centrality range.

Note, however, that since hydrodynamics is expected to be more reliable at low transverse momentum, the actual value of ε_1 is most likely to lie very close to our upper bound. Thus it is possible that the two models with the largest dipole asymmetry may only need a slight tuning to achieve a correct value, while the value from the others may in fact be too low. We prefer here to be conservative in our claimed region of allowed values and leave it to future study for more stringent conclusions.

Models such as those presented here do not in general predict a significant change in dipole asymmetry with collision energy. By extracting a best value of ε_1 from these LHC data combined with hydrodynamic calculations of lower energy collisions, we can make predictions for Au-Au collisions at RHIC assuming little change in the average dipole asymmetry in a centrality bin. Since the change of ε_1 with collision energy predicted by each current Monte Carlo model is much smaller than the range spanned by the various models, this prediction is more reliable than any obtained by assuming a particular model for the initial conditions. These are presented in Fig. 4. The value of ε_1 at LHC is obtained by taking the best fit to the experimental v_1 for $p_T < 1.5$ GeV/c, which is the range where hydrodynamics agrees best with data [29]. Our calculations use $\eta/s = 0.16$ both at LHC and at RHIC, but the extrapolation from LHC to RHIC depends very weakly on the assumed value of η/s [30].

These predictions are compatible with the attempted extraction of v_1 [17] from a much more limited set of correlation data at 20–60% centrality released by the STAR collaboration, but a dedicated analysis by one of the experimental collaborations at RHIC will allow for a much more precise test, including centrality dependence.

IV. CONCLUSIONS

We have shown that the first Fourier component of the two-particle azimuthal correlation measured at LHC, $V_{1\Delta}$, can be explained by collective flow, much in the same way as higher harmonics, after the correlation from momentum conservation is accounted for. We have thus obtained the first measurement of directed flow, v_1 , at midrapidity at the LHC. This experimental result was compared with the first viscous hydrodynamic calculation of directed flow. v_1 was found to have a weaker dependence on viscosity than v_2 and v_3 , which allows for the first time a tight constraint to be placed directly on the geometry and fluctuations of the early-time system, and which rules out certain current theoretical models. The extracted values of the dipole asymmetry of the initial conditions then allow for predictions to be made for directed flow at midrapidity in lower-energy collisions at RHIC, which were presented.

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